



## Coherence times and Rabi oscillations in $\text{CaWO}_4:\text{Cr}^{5+}$ crystal

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### ABSTRACT

The coherence times of dopant pentavalent chromium ions in  $\text{CaWO}_4$  single crystal (0.0006 at.%  $\text{Cr}^{5+}$ ) were investigated both theoretically and experimentally. Temperature dependences of spin–lattice relaxation time  $T_1$  and phase memory time  $T_M$  were measured in the temperature range 6–30 K at high (94 GHz, W band) and low (3.5 GHz, S band) frequencies of electron spin resonance. It follows from  $T_M$  calculations that phase relaxation of  $\text{Cr}^{5+}$  ion arises mainly from magnetic dipole interactions between the chromium ions.

Anomalous fast damping of Rabi oscillations is detected in both S- and W-band experiments. It is shown that this phenomenon is caused by microwave field inhomogeneity inside the resonator. Relations between the damping time of Rabi oscillations, Rabi frequency and the crystal sample size are obtained. Lumped-element resonators and smaller sample dimensions are suggested to lower spin dephasing during transient nutations.

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### 1. Introduction

The fundamental obstacle to successful implementation of a quantum computer is decoherence problem [1]. The quantum bits (qubits) must be put into such environment that their behavior is coherent while they are manipulated during quantum computation process. One possible realization of qubit is an electron spin operable with the application of magnetic field flipping pulses [1–3].

Recently, paramagnetic ions diluted in diamagnetic solid matrices have been proposed as possible qubit implementations, namely, rare earth [4–6] and transition metal ions [7–11]. The spin manipulation in such systems is achieved by application of short microwave (MW) pulses as part of electron spin resonance (ESR) experiments. Due to highly elaborated experimental techniques available in the field of magnetic resonance and relatively short qubit switching times such implementations are advantageous.

One of the most famous effects in magnetic resonance where quantum coherence manifests itself is the electron spin-echo (ESE) phenomenon. The resultant echo amplitude is lessened by irreversible loss of magnetization during the time between and after the pulses of the spin-echo sequence (i.e., in the absence of MW magnetic field). Here the time of application of resonant MW field is limited by the duration of the pulse, which is much less than phase coherence time  $T_M$ . In case of sufficiently small dopant

concentrations,  $T_M$  can exceed 100  $\mu\text{s}$ , along with the number of coherent single-qubit operations  $Q_M$  reaching  $10^4$  [6].

In quantum computation, one needs to apply sufficient amount of successive MW pulses. Thus, apart from  $T_M$ , it is crucial to know the spin coherence time during the spin transient nutation. The measure of such coherence is the damping time  $\tau_R$  of so-called Rabi oscillations (or transient nutations) [12]. These are quantum oscillations resulting from coherent absorption and emission of photons under the application of a long resonant MW pulse. The number of coherent single-qubit operations is defined as  $Q_M = \Omega_R T_M / \pi$ , where  $\Omega_R$  is Rabi frequency. Up to now, there is a considerable number of publications indicating anomalously fast damping of Rabi oscillations (RO) of paramagnetic impurities diluted in crystal matrices. Probably the first observations were carried out for  $E'$ -centers in glassy silica and for  $[\text{AlO}_4]^\circ$  centers in quartz [13–15]. They revealed the peculiar linear dependence of  $\tau_R^{-1}$  on  $\Omega_R$ :

$$\tau_R^{-1} = \frac{1}{2} T_M^{-1} + \beta \Omega_R, \quad (1)$$

with the dimensionless coefficient  $\beta \sim 10^{-2} \div 10^{-1}$ . Apart from [13–15], the anomalous damping of RO was observed recently in  $\text{Er}^{3+}$ -doped [4,5] and  $\text{Yb}^{3+}$ -doped [6]  $\text{CaWO}_4$  crystals, in molecular magnets  $\text{Fe}_4$  [8] and  $\text{V}_{15}$  [9,10], in  $\text{MgO}:\text{Mn}^{2+}$  [7] and in  $\text{K}_3\text{NbO}_8:\text{Cr}^{5+}$  [11]. For ordinary experimental conditions, the second term in (1) prevails over the first one. For appropriate MW field intensities, the ratio  $T_M/\tau_R$  may be as high as  $10^3$  [6]. The term  $T_M^{-1}/2$  is explained in the framework of Bloch model [13]. However, to the

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